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ADVANCED CONCEPTS FOR LIGHTWEIGHT TORPEDO PROPULSION.(U)

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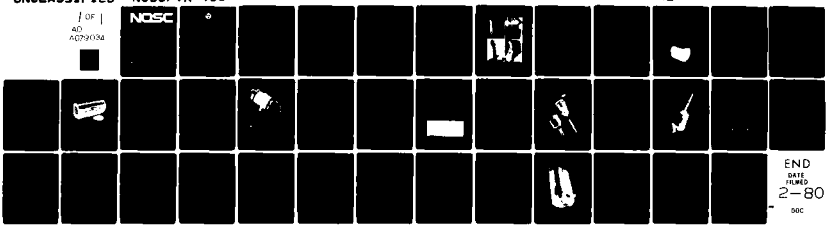

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ADVANCED CONCEPTS FOR LIGHTWEIGHT TORPEDO PROPULSION

RK Gottfredson

August 1979

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NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

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SL GUILLE, CAPT, USN
Commander

HL BLOOD
Technical Director

ADMINISTRATIVE INFORMATION

This report was prepared in the Propulsion Design Branch, Torpedo Division, of the Torpedo and Countermeasures Department.

Released by
RL Matthews, head
Torpedo Division

Under authority of
MO Heinrich, head
Torpedo and Countermeasures Department

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Exploratory development for lightweight torpedo propulsion has continued through the years to support development of electric, open-cycle thermal and closed-cycle thermal systems. Several systems representative of these propulsion types are being pursued both by Naval Laboratories and by industry which are potential candidates for a new generation of lightweight torpedoes. Four of the most promising systems are discussed: An improved open-cycle monopropellant propulsion system; a closed-cycle system, known as the Stored Chemical Energy Propulsion System (SCEPS); and two battery-electric propulsion systems. One of the battery systems is somewhat

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reminiscent of the older seawater battery system, but has far superior energy densities. The second battery system is completely closed and has the potential of being very simple, also with very high energy density. Advantages and disadvantages of the four systems are discussed, followed by discussions of the energy sources, prime movers, speed reducers, and systems considerations. Background information on the seawater battery electric and earlier open-cycle systems is also included.

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A

INTRODUCTION

Historically torpedoes have been powered by both electric and thermal propulsion systems, the trend being to shift from one to the other as the relative merits changed due to changes in technology and operational requirements. Two decades ago torpedo propulsion was dominated by electric systems primarily because of their simplicity. Increasing demands for higher speed and longer endurance soon exceeded their capabilities so attention was focused on thermal systems, in particular open-cycle. The open-cycle powered Mk 46 series of lightweight torpedoes came into being in the mid-1960's, and still exists today.

There are many criteria that must be evaluated when attempting to find the best propulsion system candidate for an application such as a torpedo. Some of them, such as high energy content on a weight basis, low cost, and reliability, are much the same as those considered for many applications. Other factors such as volume performance, toxicity, and other safety hazards should receive added emphasis because of the environment in which a torpedo is stored, handled, and used. Also, present and future launch platforms place constraints on the torpedo diameter, length, weight, and shape. These include the surface vessel torpedo tube (SVTT), fixed-wing aircraft, helicopter, and rocket launcher (ASROC) (Fig. 1).

But the one thing that has the most impact on making the torpedo propulsion requirement different from most other applications is that, after satisfying all of the above criteria, it must then be able to deliver its entire energy content at an extremely high power level in, typically, 10 minutes.

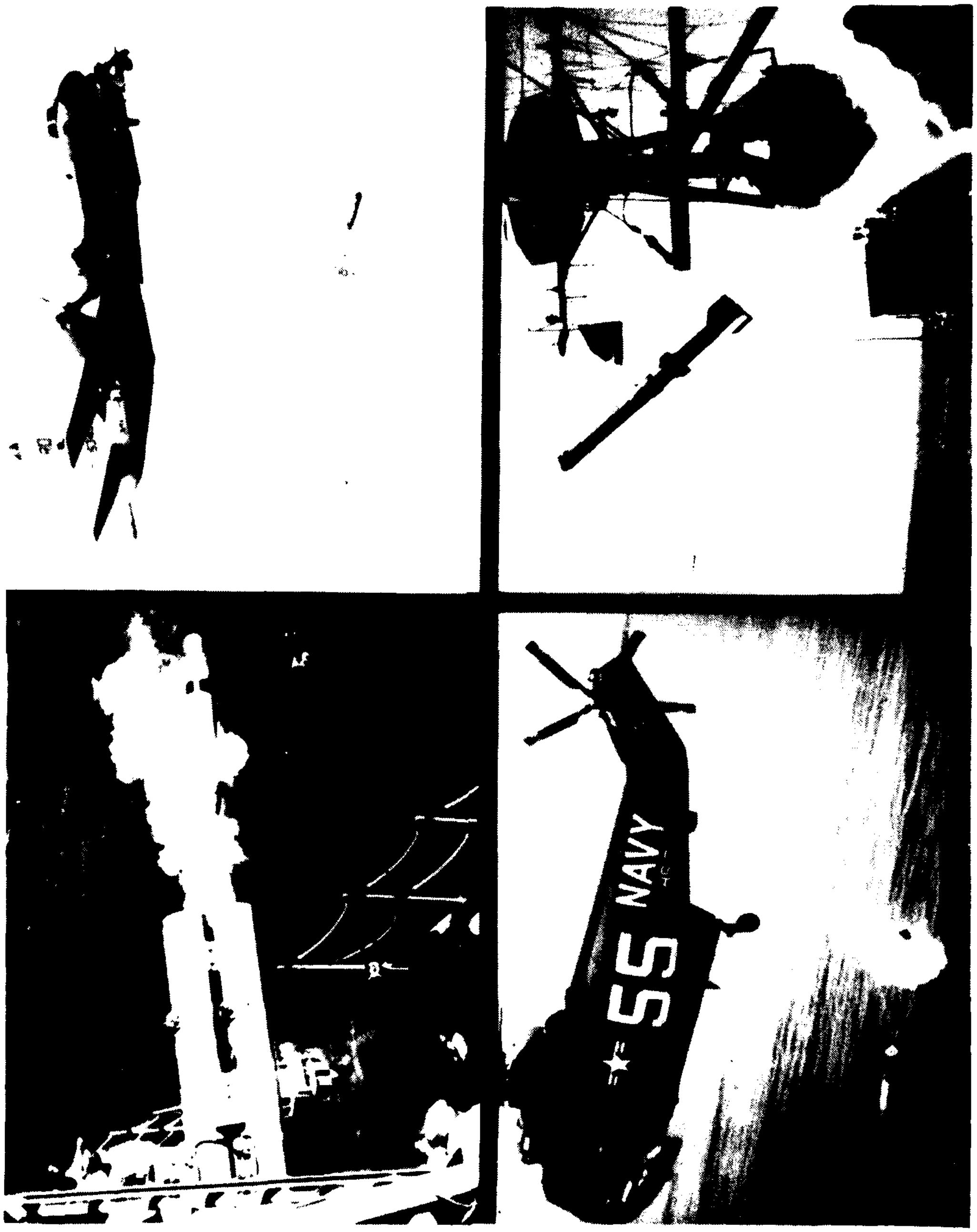


Figure 1. Lightweight torpedo launch platforms.

PROPULSION SYSTEM TYPES

The multi-platform ASW (antisubmarine-warfare) torpedo is a lightweight torpedo which weighs about 272 kg (600 lb) and is 0.32 m (12.75 in.) in diameter by about 2.74 m (9 ft) long. Such a weapon is two to three times as demanding as the heavyweight torpedoes with respect to energy density since the former may be as large as 0.53 m (21 in.) in diameter by 6.1 m (20 ft) long. There are four generic types of propulsion systems that can be considered for lightweight torpedoes: seawater battery electric, open-cycle thermal, high-rate battery electric, and closed-cycle thermal. All four types have advantages and disadvantages, and the relative merits of the systems will change with the specific application and operating constraints. Considerations of interest include:

- Performance
  - Power and Energy Densities
- Cost
  - Development
  - Life Cycle
- Detectability
  - Radiated Noise
  - Wake
- Multispeed Capability
- Interference with Vehicle Sensor Systems
- Safety
- Reliability
- Simplicity for Maintenance and Overhaul
- Vehicle Recovery
- Technical Risk

The system characteristics can easily be summarized by the following:

a. Seawater Battery Electric System:

1. Least complicated;
2. Insensitive to depth with only very slight wake due to H_2 generation;
3. Heaviest, therefore most difficult to float in exercise configuration;
4. Considerable past experience.

b. Open-Cycle System:

1. Somewhat more complicated than seawater battery electric system;
2. Depth sensitive with relatively large gaseous wake;
3. Lightest at end of run after fuel is consumed and many cases will float in exercise configuration;
4. Considerable past experience.

c. High-Rate Battery Electric:

1. Can be complicated;
2. Little or no H_2 generation;
3. Generally heavy – some configurations potentially lightweight;
4. Least developed.

d. Closed-Cycle Systems:

1. Generally most complicated;
2. Insensitive to depth and wakeless;
3. About same weight as open-cycle system but more difficult to float in exercise configuration since reaction products are stored;
4. Most competitive for high velocity, large size, and long range.

ELECTRIC SYSTEMS (BATTERIES)

Electric propulsion is a very important concept for Lightweight Torpedoes with its potential for low noise and negligible wake, which would thus enhance performance of the acoustic guidance system. Historically these attributes have been enhanced by the simplicity of electric systems, which are thus inherently reliable. Battery-electric systems have been used in past lightweight torpedoes, and substantial exploratory and advanced development is underway on improved electric components.

MAGNESIUM-SILVER CHLORIDE-SEAWATER BATTERY

Seawater battery technology has been pursued at the Naval Ocean Systems Center (NOSC), San Diego, California, to the point where a 120-kW battery can be packaged in a 0.87 m (34.5 in.) long section weighing about 147.6 Kg (325 lb) (an improvement in energy density of about 20%). It is a simple system, not requiring mixing of carried electrolyte, heat exchanger, recirculation pump and/or gas separator. In addition, this capability is state-of-the-art.

For torpedo applications this battery uses a pile type construction with glass beads to separate the magnesium alloy anode from the silver chloride cathode so that the seawater electrolyte can flow up through the cells in order to cool the battery and remove the reaction products (primarily $MgCl_2$ and H_2 gas) (see Fig. 2). Seawater batteries have been used for many years, both here and abroad. Significant improvements have been demonstrated in the newest seawater battery, which uses an improved magnesium alloy (AP-65) to get 20% higher voltage than with the previous AZ-61, and simplified electrolyte recirculation and voltage control, which is accomplished by means of a seawater scoop and jet pump as shown in Fig. 3.

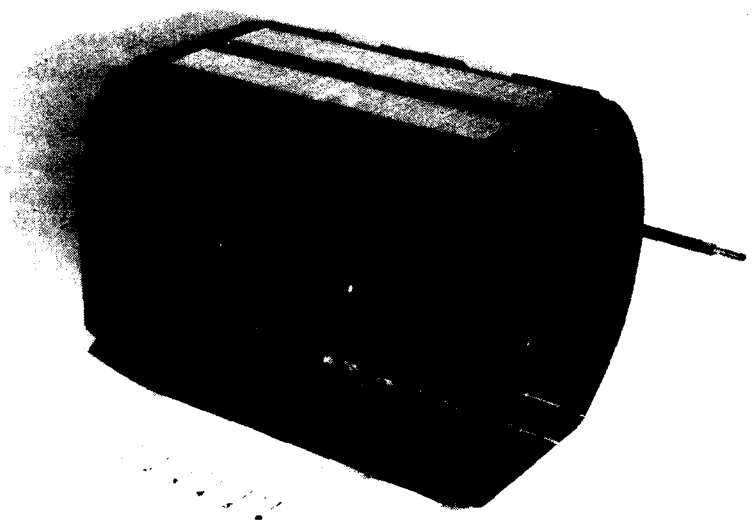


Figure 2. Seawater battery cartridge.

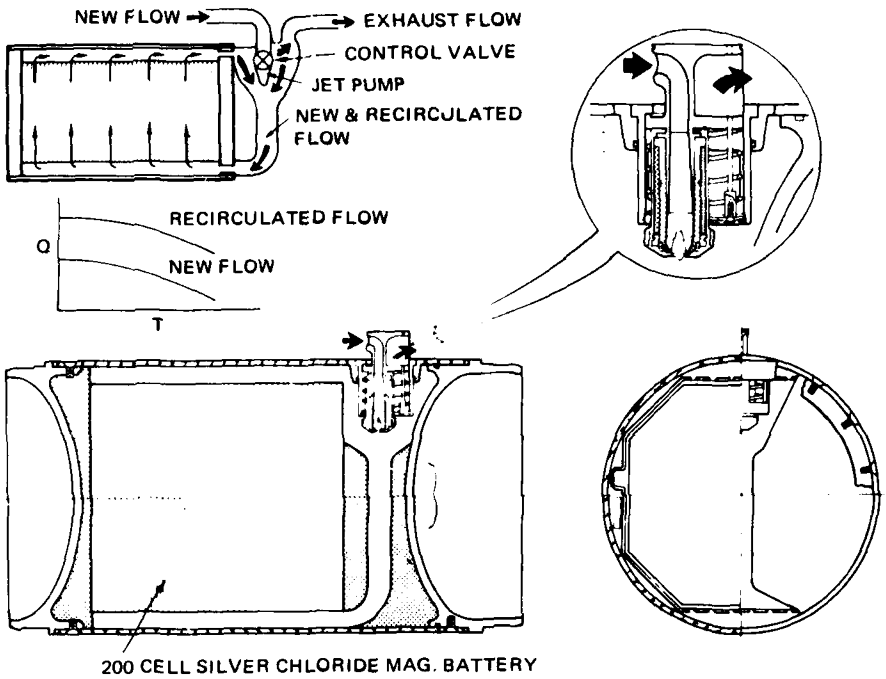


Figure 3. Seawater battery system.

A 200-cell battery that gives nominally 55 kW has been used to propel the RETORC (Research Torpedo Configuration) I test vehicle in ten sea runs. Two of these units have been stacked together and discharged in a captive test facility that simulates free-running conditions to give 110 kW, with a single jet pump providing the recirculation and voltage control. Energy density would be 58 W-hr/lb of battery cartridge weight. This would be reduced to 40 W-hr/lb when the entire battery section of the torpedo, including the shell, bulkheads, pump, and controls, are included. The major advantages of the seawater battery are that it is a well-developed technology, it has a constant voltage output with high current density, is capable of long-term storage, and is competitive on a volume basis. However, due to the large number of cells required and the 65.8 Kg (145 lb) of silver contained therein, it is a very heavy system. It also requires seawater flow controls, has some H_2 gas evolution, and sustains some performance degradation in low-salinity and cold seawater.

ALUMINUM-SILVER OXIDE BATTERY

The aluminum-silver oxide (AlAgO) battery invented at the Naval Underwater Systems Center (NUSC), Newport, R.I., has been pursued as a candidate propulsion system for lightweight torpedoes because of its projected high energy density. Original estimates placed it at twice that of a magnesium-silver chloride seawater battery, and subsequent developments indicate that this system will be only slightly less dense than anticipated.

This battery is of the pile type construction, so that a total voltage is achieved by assembling a group of duplex electrodes in series connection. Unlike the magnesium-silver chloride seawater battery, parallel connected groups of electrodes are not required because of the flat polarization curve of the Al-AgO battery at very high current densities. The duplex electrode consists of an AgO cathode and an Al anode connected by a metallic foil conductor. Glass beads are imbedded in the porous silver electrode before formation to serve as a spacer between the electrodes of a given cell. This allows a free flow of electrolyte (KOH in seawater) in the cell during operation.

Thus far the battery has operated best at 82.5°C (180°F). At this temperature H_2 evolution is kept at a minimum; however, it will double for each 10°C rise in temperature. The electrolyte flow is about 190 liters/min, and the electrolyte is maintained at a minimum concentration of 15% KOH during the course of discharge. Typical discharge current densities have been on the order of 770 to 930 mA/cm^2 (5-6 $A/in.^2$).

Recent developments in aluminum-silver oxide battery studies indicate that substantial gains in energy density can be realized by operating at increased current densities and temperatures. Based on tests at 1400 mA/cm^2 (9 $A/in.^2$) and at temperatures to 105°C (220°F), a 30% improvement is projected. The Naval Underwater Systems Center's experience with raceway modeling and breadboard electrolyte testing, when combined with new component design concepts, will provide additional packaging gains. The new system concept is projected to be two-thirds the size of the seawater battery, about 0.56 m (22 in.) long, and weigh approximately 91 Kg (200 lb) (see Fig. 4).

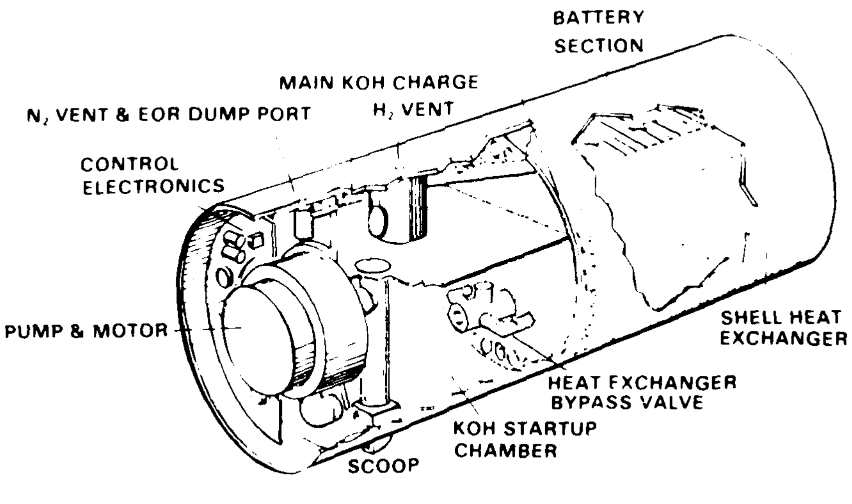


Figure 4. AlAgO battery system.

The major advantages of the Al-AgO battery are that it is capable of very high discharge rates, has very good volume performance, is capable of very high current densities with high cell voltage, has only 1/6 the H_2 evolution of the seawater battery, and is capable of long-term storage. Conversely, it contains about 41 Kg (90 lb) of silver and requires a somewhat complex auxiliary system consisting of heat exchanger, recirculation pump, and gas separator. It also requires a mechanism for initial mixing of electrolyte and subsequent maintenance of the proper KOH concentration. Advanced Development will also be necessary before Fleet use can be considered.

LITHIUM THIONYL CHLORIDE BATTERY

Another energetic system now under development is based on lithium and thionyl chloride ($Li\text{-}SOCl_2$). On a weight basis lithium is the most energetic element in the electromotive series. The high lithium potential is unsuitable for use in ordinary aqueous systems due to its chemical reactivity with water. It must, therefore, be used in non-aqueous electrolyte systems, which have been the subject of concentrated research since the early 1960's as the avenue to develop a reliable high-energy lithium battery.

Only preliminary investigative work in the U.S.S.R. and Warsaw Pact countries is reported in the technical literature, but extensive research using thionyl chloride by GTE starting in 1970 has been expanded by Mallory, EIC, Honeywell, Altus, Electrochimica, and Union Carbide in the U.S., by S.A.F.T. in France, Japan Storage Battery Company in Japan, and Tadiran in Israel.

The theoretical gravimetric energy density of $Li\text{-}SOCl_2$ is very high at 1470 W-hr per kg. This calculated value is based on the reaction:

$$4\ Li + 2\ SOCl_2 \rightarrow 4\ Li\ Cl + S + SO_2 \quad ; \quad E^\circ = 3.65$$

In practice very large $Li\text{-}SOCl_2$ cells at low rates have achieved energy densities of nearly 600 W-hr/kg, and high rates of discharge (300 mA/cm^2) have been demonstrated in sizes of a few centimeters. Also, 11-in.-diameter cells in 10-cell bipolar stacks have recently been discharged at energy densities suitable for high-rate torpedo applications.

Safety is a major concern in all uses of batteries. In the past some configurations of the $Li\text{-}SOCl_2$ system have exhibited an explosion hazard during abuse testing. However, there are now two $Li\text{-}SOCl_2$ batteries on the market which are claimed to be free of explosion hazard in most conditions of abuse. Most of the design features are proprietary and/or have patents pending and the Safety Mechanisms are only partially disclosed to the public, so this somewhat limits predictions of performance.

The largest prism-shaped cells built to date are low-rate cells designed to deliver in excess of 12000 A-hrs. The largest disc-shaped cells constructed to date are those built under a program directed by NOSC. These 0.43 m (17 in.) diameter 1500 A-hr cells are designed to deliver between 2 and 3 mA/cm^2 for 100 hours. However, higher rates can be achieved for shorter periods of time. A current density of greater than 100 mA/cm^2 has now been demonstrated in 11-in.-diameter cells, indicating a successful torpedo configuration may soon be feasible.

As indicated, the data base for a high-rate $Li\text{-}SOCl_2$ battery is inadequate in the public domain to allow highly accurate system projections. However, polarization data and waste heat measurements of batteries are currently being taken. Information on the wet-life of an active (as opposed to a reserve) configuration is also being collected.

With the currently available data base a projection has been made by NOSC that a packaged reserve configuration which meets storage and safety requirements is feasible in a length of about 0.67 m (24 in.) with a corresponding weight of 82.8 kg (171 lb). A reserve battery system was selected for this high-rate torpedo study because it reduces the risk of anode passivation and energy loss via internal leakage during long periods of storage. A mockup of this system is shown in Fig. 5.

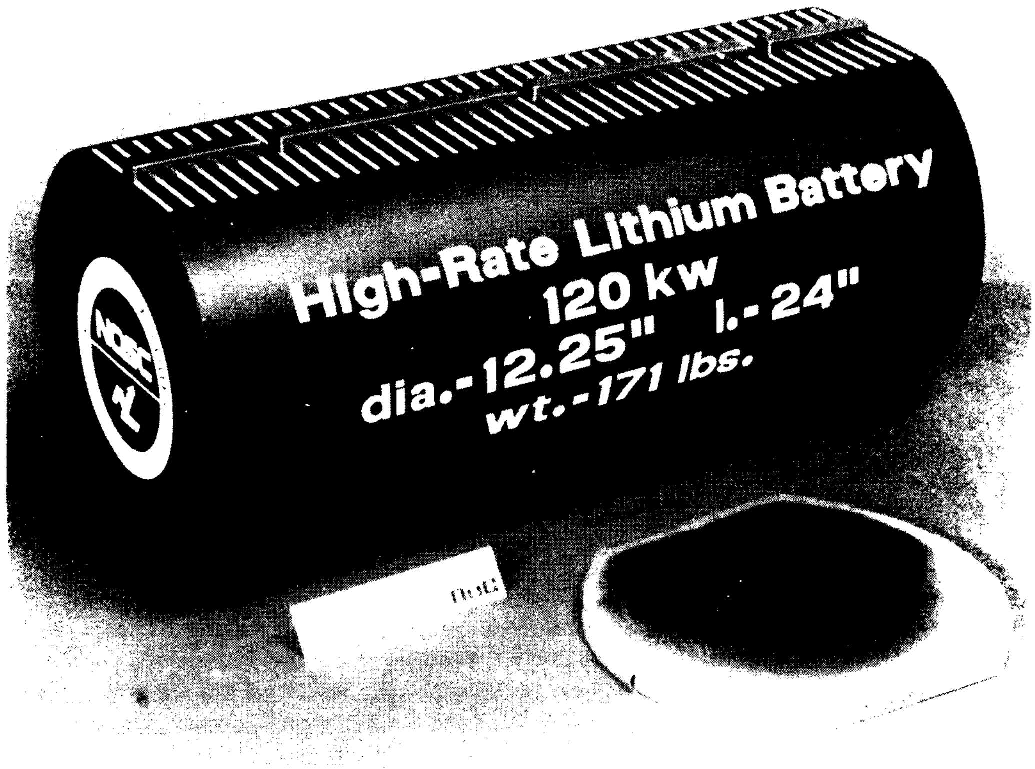


Figure 5. Li-$SOCl_2$ battery and cell mockup.

CONCLUSIONS

The two high-rate battery systems reviewed here briefly have the potential of meeting the lightweight torpedo requirement. The Al-AgO battery has been brought from a laboratory idea to a nearly demonstrated system in a very brief time span and it is very competitive on both a weight and volume basis. Recent extrapolations of experimental data project a substantial growth potential for the Al-AgO battery. Current estimates predict that a length reduction on the order of 30% with a corresponding weight decrease may be possible. However, it does require a large amount of auxiliary equipment for heat exchanger, gas separator, etc. It also contains a substantial amount of silver and is noticably more complex than previous torpedo battery systems, which generally have not required heat exchanger, gas separator, and electrolyte mixing and maintenance.

The major advantages of the Li-$SOCl_2$ battery are that it is very energetic on both a gravimetric and volumetric basis; the materials of construction are plentiful, relatively inexpensive and non-strategic; and it is a potentially simple system that is completely wakeless. The system should continue to be the subject of intensive and extensive development.

Many of the limitations of Li-$SOCl_2$ for high-rate applications have been mentioned above. They are primarily the lack of public design data on how to produce efficient cathode (current collector) material; techniques required to achieve reasonable levels of safety under abuse conditions; and waste heat production as a function of discharged rate.

ELECTRIC SYSTEMS (MOTORS)

Continuing work has been supported by both NOSC and NUSC on the development of high-power-density motors. Development contractors have included Westinghouse, General Electric, Bogue, TRW, Lear Siegler, Arma Bosch, Leland, Garrett, and Sundstrand. Motor configurations have involved single-output-shaft conventional designs, counter-rotating output shafts, and brushless machines using electronic commutation. While substantial work has been supported on the latter (brushless) concepts because of the high performance potential, so far none of that work has resulted in an acceptably reliable machine. The problems encountered have been related to the electronic circuitry, primarily in the silicon-controlled-rectifiers (SCR) and high-power transistors. Continuing improvements in these devices will make this approach more attractive in the future.

The most commonly used type of motor in torpedo applications has been the counter-rotating configuration, however, the highest power densities achieved in a reliable motor to date have been with high-rpm, conventional, dc, single-shaft machines. These are typically used with gear reduction to drive counterrotating propellers. Power densities of 6×10^{-4} to 7×10^{-4} kg/W (1.0 to 1.2 lb/hp) are achieved (including gearbox).

DC MOTOR AND GEARBOX

Recent work on a dc motor and gearbox assembly for a lightweight torpedo developed in conjunction with the seawater battery described previously has yielded a compact, quiet and reliable machine (Fig. 6). The motor is a compound-wound machine that operates at a design speed of 9000 rpm. Motor efficiency ranges between 85 and 90 percent (hot versus cold). The motor alone is 0.18 m (7-1/4 in.) in diameter by 0.3 m (11 in.) long and has proven very reliable, with no maintenance being required for 10 to 20 runs.

The gearbox was developed separately, but designed specifically for this motor. It converts the 9000 rpm motor input to ±1800 rpm on counterrotating output shafts. The main body is 0.15 m (5.8 in.) in diameter and the entire gearbox weighs only 4.5 kg (9.9 lb) dry (oil splash lubrication). It has been tested to 110% power, with no failures or malfunctions of any kind occurring. Operation is smooth and quiet, with a measured transmission efficiency of 97.5%. Planetary stages are employed with 30-deg helical gear teeth used throughout for quietness. Figure 7 shows the motor/gearbox assembly in conjunction with a seawater battery developed for an experimental torpedo.

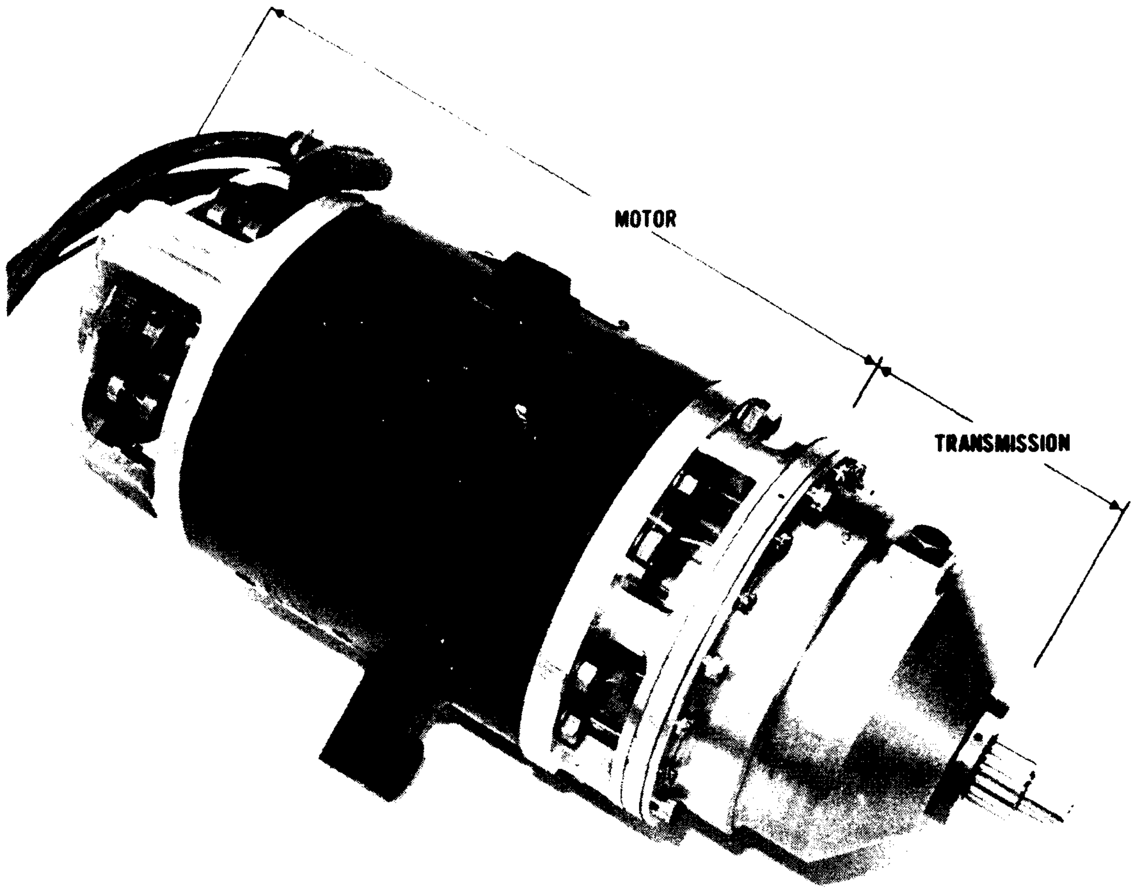


Figure 6. dc motor/gearbox.

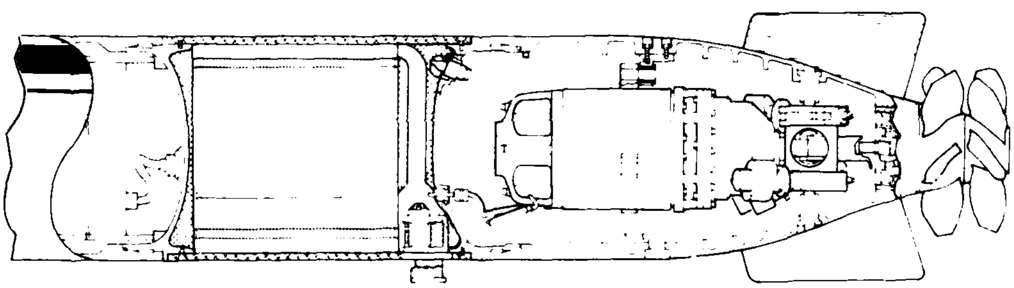


Figure 7. Seawater battery propulsion system.

BRUSHLESS, ELECTRONICALLY COMMUTATED MOTORS

Some of the more significant new developments in motor technology include very high-coercive-energy permanent magnets, new and better power switching semi-conductors, and very low-loss magnetic iron.

High-energy permanent magnets (samarium cobalt) are now being made in production quantities large enough to accommodate motors to 150 kW (200 hp). These new magnets will occupy about one-tenth the motor volume as compared with conventional magnets, which take about one-half the volume. These magnets also have lower losses and less heating, thereby contributing to highly efficient motor designs.

Motors have long been driven and controlled by semi-conductor power conditioners. These semi-conductors have largely been SCRs, which generally have been less efficient and less controllable than the high-power transistors which are now just coming on the market. It has long been known that mechanical commutation of dc machines with no apparent arcing at the carbon brush contact improves efficiency and reliability. This is accomplished through careful design of fields and poles and is limited to electrically excited field type motors. With the advent of power switching transistors (and better SCRs) and small powerful permanent magnets, currents can be turned on with fairly precise time control so that circuits can be designed to produce the best interaction between the current in the armature and the permanent magnet field. The process is termed "torque angle" control and results in the highest motor torque-to-armature current ratio.

The induction motor is still a strong contender for torpedo applications. The additional losses of this motor are only on the order of two or three percentage points in efficiency, while the size reduction and reliability are probably improved. The millions of induction motors in commercial use have service records unequaled by any other motor type.

The most recent torpedo motor development effort has been under the auspices of the Naval Sea Systems Command through a contract administered by NUSC and awarded to Airesearch Manufacturing Company, a division of Garrett Corporation, in April 1977. The motor system developed by Airesearch is a counterrotating permanent-magnet rotor, direct-drive motor, controlled by a solid state electronics package that consists of a chopper, three-phase inverter, associated logic, and power supply as shown schematically in Fig. 8.

High-technology transcalent transistors manufactured by RCA were selected for the early version of the chopper, but subsequent units utilized Motorola production transistors, which were not available at the beginning of the program. Performance of the latter units has been demonstrated to 90% of the specified requirement.

The motor and electronics assembly have been tested in the contractor's plant at various power levels as a system, with the best performance to date being a 10-minute run at the 86-kW power level. The rotating machine has been a reliable workhorse during the more than 350 hours of test time, requiring only minor maintenance after initial assembly. Although the system has not been tested at full rated power, each of the component parts has, on an individual basis, demonstrated the capability.

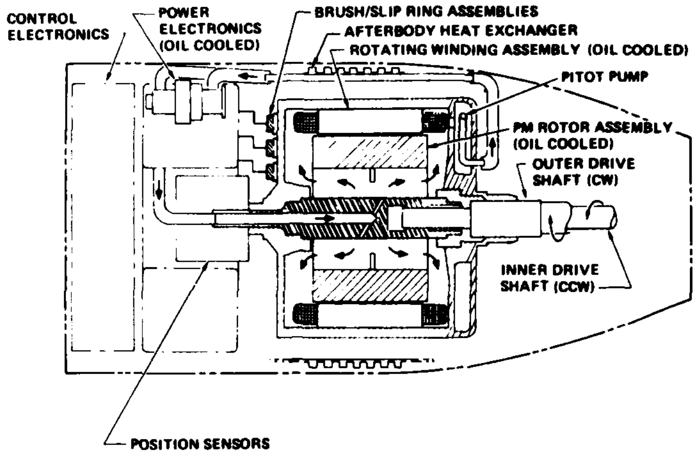


Figure 8. Electronically commutated ac motor.

ELECTRIC SYSTEMS SUMMARY

Electric propulsion systems have an extensive background in Fleet torpedoes and, over the years, have enjoyed continuing exploratory development. Simplicity and reliability has been a primary attribute, along with a high degree of safety. Electric systems require little or no maintenance, either during storage or when being turned around between runs. Related to both maintainability and reliability, and just recently receiving consideration as an important factor, is that electric systems can be externally checked to a high degree in order to monitor operability and readiness (resistance checks, turn rotating equipment with external power supply, etc.) In general, electric systems should be cost competitive with the simpler open-cycle thermal systems. However, definite cost statements cannot be made without comparing specific systems. Also, reviewers often have the opinion that electric systems are inherently quieter than thermal systems, which have large numbers of moving parts, and potentially noisy fluid flow and combustion gas dynamics phenomena.

OPEN-CYCLE MONOPROPELLANT THERMAL SYSTEMS

The open-cycle engine/turbine using a monopropellant fuel is the simplest possible thermodynamic cycle, wherein only one fluid, the monopropellant, is burned in a combustion chamber and the reaction products expanded through an engine or turbine directly against the ambient sea. Expansion engines with external combustion do not require a compression phase or internal ignition system and every stroke becomes a power stroke. As the operating depth increases, the combustion pressure must also be increased to maintain a given pressure ratio across the engine and, hence, a constant power output. Engine and combustion technology has reached a point where operation against depth pressure does not present a serious problem. Experimental work at NOSC has demonstrated sea runs in a lightweight test vehicle wherein combustion pressures to 4.14×10^7 N/m^2 (6000 psi) were sustained for efficient operation to depths of several hundred meters.

Monopropellant/open-cycle engine systems are common in the Fleet today, being used in the latest air-launched torpedo and, more recently, in submarine-launched torpedoes. These torpedoes use the monopropellant Otto Fuel II. In addition, other monopropellants are currently being investigated under exploratory development programs.

Otto fuel was developed in-house at the Naval Ordnance Station (NOS), Indian Head, MD. It is very safe and inert, is currently in the Navy logistical system, and a great deal of background experience exists. Weight performance is good, however, Otto fuel leaves a sizable wake, being less than 25% condensable.

PISTON PRIME MOVERS

Mk 46-1 Engine

The MK 46-1 lightweight torpedo engine is a 63.4 kW (85 hp) barrel-type piston expander which incorporates a double rise cam and five pistons as shown in Fig. 9. This combination results in ten power strokes per revolution for a total displacement of 9×10^{-5} m^3 (5.5 in.^{3}).

Figure 9. MK 46/1 engine assembly.

Operating pressures are up to 2.41×10^7 N/m^2 (3500 psi). Counterrotation permits the engine to directly drive two propellers at about 2200 rpm per shaft. The engine weighs approximately 11 kg (25 lb).

H-4 Engine

This lightweight, 74.6 kW (100 hp), torpedo engine was originally designed for deep operation. Engine design is wobble plate type with six pistons as shown in Fig. 10. The unique drive mechanism consisting of wobble plate, needle bearings and cam follower can be easily seen. Total displacement is again 9×10^{-5} m^3 (5.5 in.^{3}) however, operating pressures are now up to 4.14×10^7 N/m^2 (6000 psi). The engine counterrotates with a relative shaft speed of approximately 5000 rpm. The engine weight is about 15 kg (33 lb). The higher operating pressure of this engine, combined with optimized valve timing, yields a desired lower fuel consumption.

Several design breakthroughs have been accomplished in the development of the H-4 piston propulsion system, and one of the more important of these has been in the combustion chamber configuration. In this design, the combustion chamber has been significantly reduced in size from the Mk 46 Mod 1 chamber from 2.2×10^{-4} m^3 to 6.2×10^{-5} m^3 (13.3 in.^{3} to 3.8 in.^{3}) so that it could be attached directly to, and hence rotated with, the conical engine valve. This has the advantage of eliminating the hot-gas face seal required in the Mk 46 Mod 1 engine and replacing it with a cold liquid fuel seal. This is especially important since combustion pressures now run as high as 4.14×10^7 N/m^2 (6000 psi), and these pressures have proven no problem for the rotary fuel seal. An additional advantage gained from reducing the chamber size is obtaining a more favorable characteristic length (L*) of 11.7 m (460 in.) as compared with 39.6 m (1560 in.) for the Mk 46 Mod 1 combustor.

In this "boot strap" system a seawater battery supplies voltage to an igniter which initiates the starter grain, generating sufficient heat and gas to rotate the engine and accessories at approximately half speed. The fuel pump then overcomes combustion pressure and fuel is injected directly onto the burning grain, "fuel crossover" is achieved and full speed is obtained.

Figure 10. H-4 swashplate engine.

Improved Swashplate Piston Engine

The objectives of this design effort were to design, fabricate and package a 120-kW (160-hp) open-cycle propulsion system in a 0.32 m (12.75 in.) diameter test vehicle, and to determine full power performance and noise characteristics.

Engine design is of the counterrotating swashplate type with seven cylinders (for smooth operation) and rotary combustion chamber. The drive consists of a wobble plate and cam follower mechanism as in the H-4 engine. It is planned, however, to eventually replace this with a gimbal arm design and to replace rolling-element bearings with journal bearings in order to further reduce vibration levels to permit utilization of an improved guidance system. Total displacement of this engine is 1.47×10^{-4} m^3 (9 in.^{3}) with operating pressures to 3.45×10^7 N/m^2 (5000 psi). It rotates with a relative speed of 5000 rpm. Figure 11 shows a picture of this engine.

For the first time in open-cycle propulsion design a serious attempt at isolation mounting was made. In this regard the accessory bulkhead and engine assembly are tied together to prevent the reaction force that tends to separate them from being transmitted to the afterbody shell. This permits the engine assembly to float on four rubber pads, two of which are shown in cross-section schematically in Fig. 12. This unique design feature is believed responsible for the very low self-noise levels that were achieved with this system.

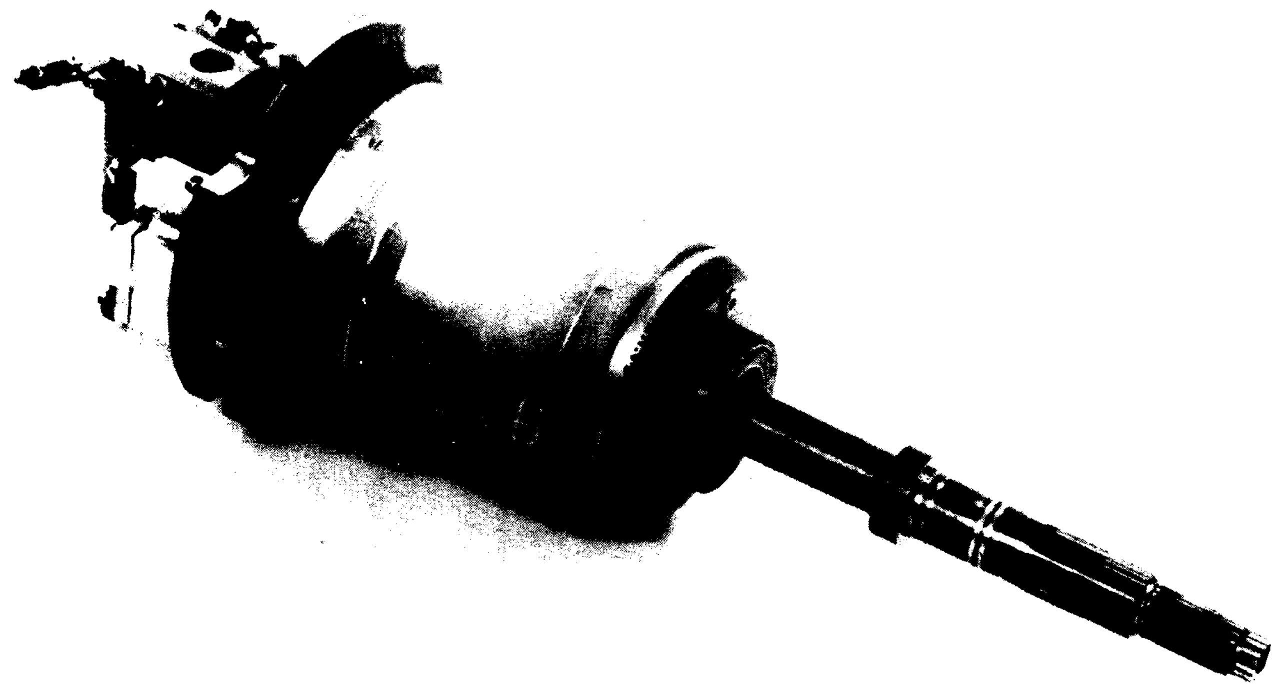


Figure 11. Improved swashplate engine.

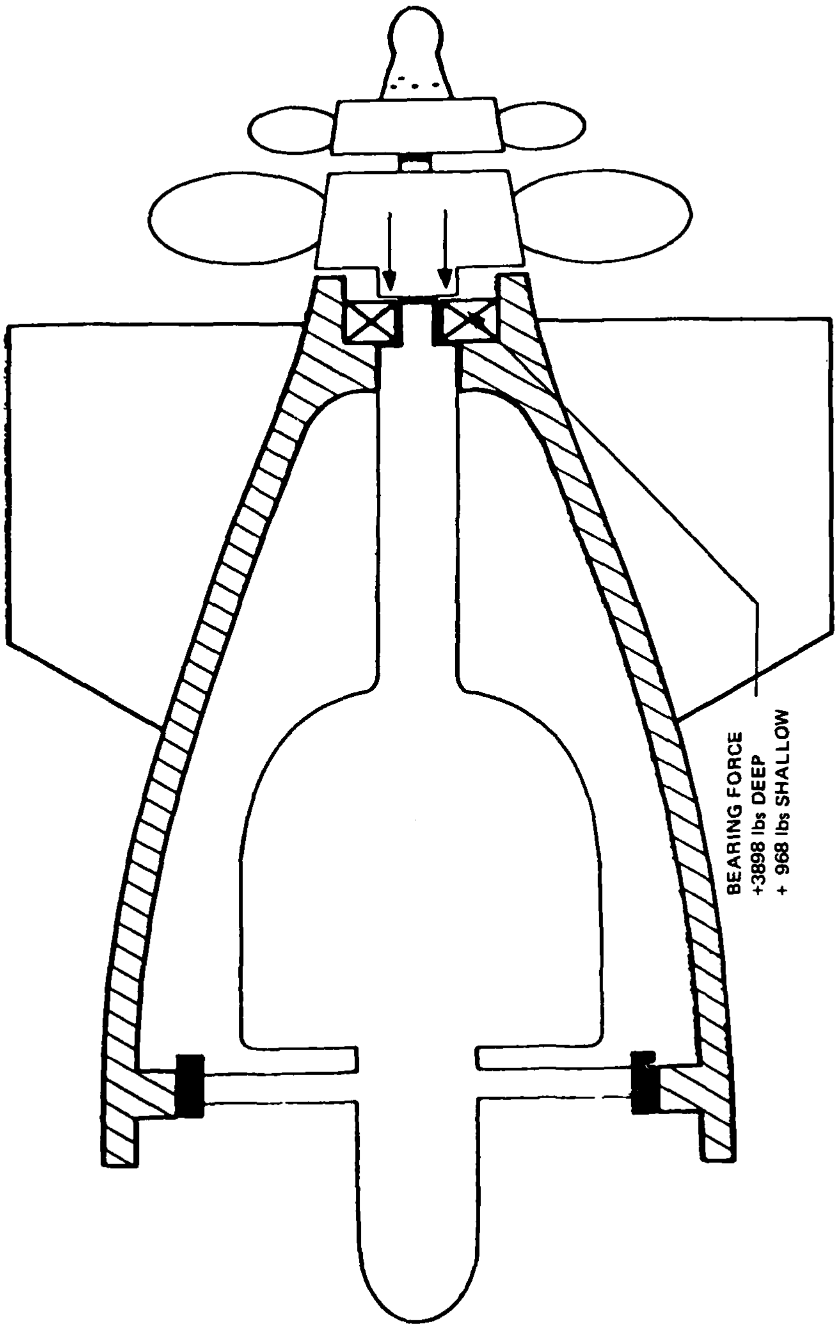
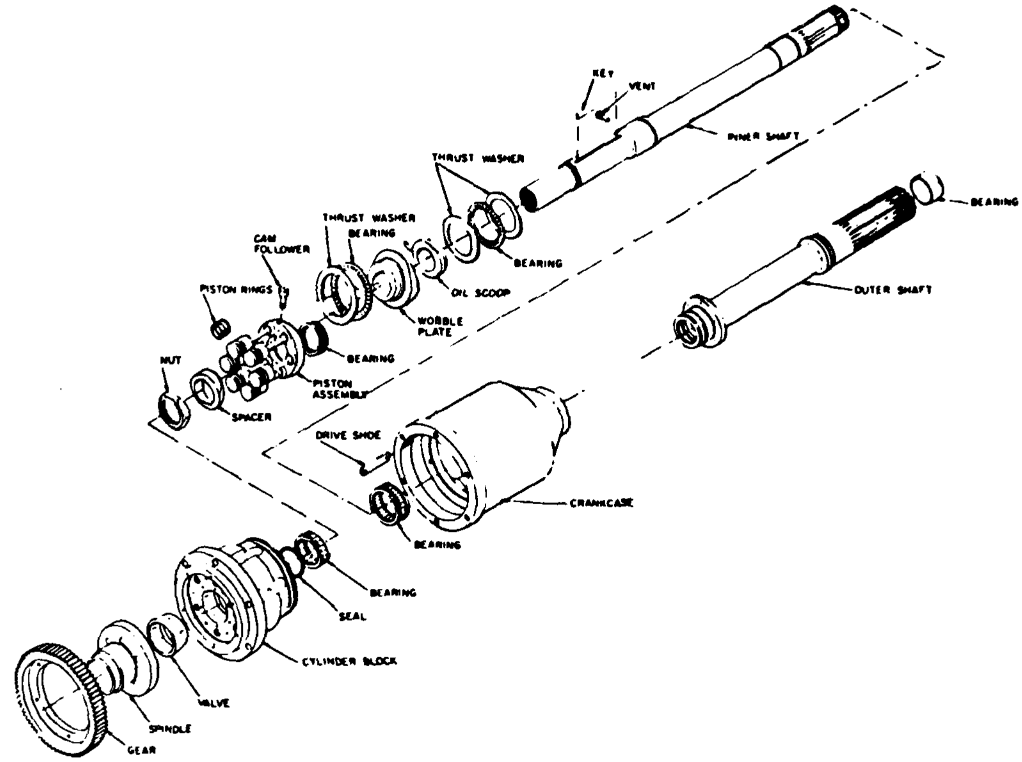


Figure 12. Open-cycle isolation mounting.

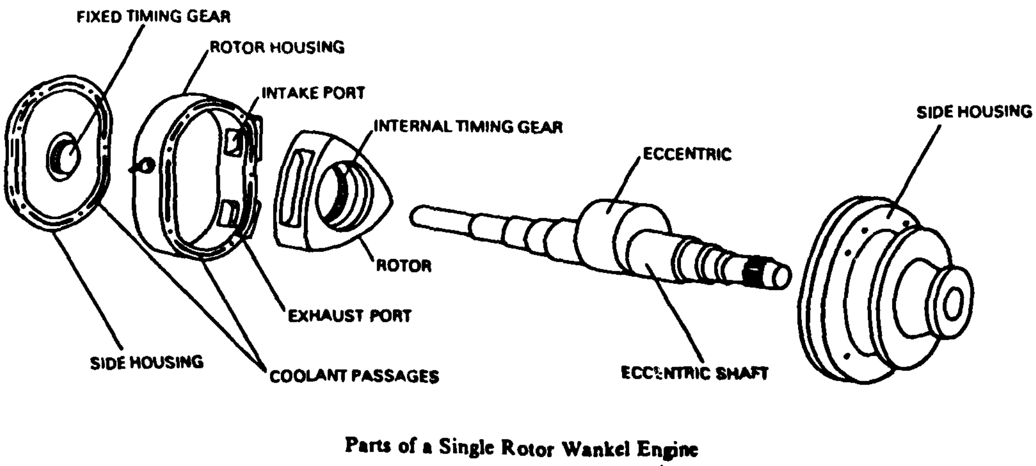
WANKEL EXPANDER

The feasibility of adapting the Wankel engine to underwater propulsion applications is currently being evaluated. When modified for use as a hot gas expander, this engine presents a promising substitute for the barrel type piston engine. It offers the potential of lower powerplant noise based on its inherent design simplicity. This is a very important consideration for homing torpedoes since target acquisition range is a function of the acoustic self-noise. The piston expanders currently used have a large number of moving components (pistons, rods, bearings, etc.) which are subjected to time-varying loads. The number of moving parts in a Wankel expander is far smaller as shown in Fig. 13. Noise reduction over the piston engine is expected by reason of balanced direct rotary motion and the reduction in the number of moving parts.

In both the Wankel and piston expansion engines the thermodynamic cycle is the same and so have the same P-V diagram. Both engines would ideally provide identical efficiency and fuel consumption, but in actuality are not the same due to differences in losses in gas sealing, mechanical efficiency, heat loss, and non-ideal flow through valving. Thus far sealing and sealing losses in the Wankel expander have proven to be the major developmental areas.



Barrel-Type Piston Engine Representative of Current Torpedo Propulsion



Parts of a Single Rotor Wankel Engine

Figure 13. Wankel/piston expander comparison.

VANE EXPANDERS

Various geometries have been proposed for vane expanders, however, only the simplest geometry has found wide usage, primarily in air motors. These expanders generally have been under 7,460 W (10 hp) and most often made in the fractional power range for air drills, impact wrenches, etc. While these vane expanders have been well developed for use with air, they have not been developed for high-temperature working fluids. General Electric, the Applied Research Lab (ARL/PSU) Penn State, and Gould, Inc. have contributed some effort toward this objective with only limited success to date.

The advantages of this type of prime mover are:

1. Rotary motion only; therefore, low vibration and potentially low noise;
2. Simple geometry and few parts; therefore, low cost;
3. High power density on both a weight and volume basis; and
4. High torque at low speed (no gearbox required).

Some of the problem areas are:

1. Sealing (leakage – as in the Wankel expander);

   (a) between vane and outer stator (a loading of the vane radially outward must be provided)

   (b) between vane and end plates

   (c) between rotor and end plates

   (d) between the vane and the slot

2. Thermal expansion and distortion creating high leakage or high friction;
3. Wear and vane chatter; and
4. Vane strength and frictional characteristics (lubrication).

If the above problems can be solved for the high-temperature working fluids, the device may be competitive; however, to date these problems mostly remain unsolved.

Figure 14 shows a schematic representation of a vane expander. Note that two inlet and outlet ports have been provided to double the power output. This type of expander, as in the Wankel, can be operated either with a single shaft output or in counterrotation.

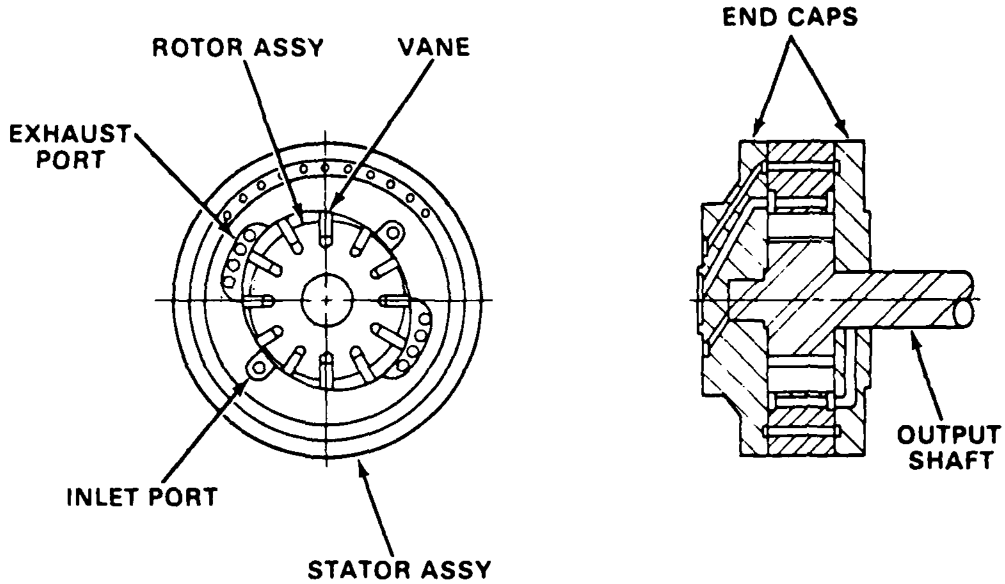


Figure 14. Vane expander.

TURBINES

The turbine system is similar to the piston engine except for the oil lubrication system required for turbine bearings and the gearbox required to reduce the approximately 100,000 rpm turbine speed to propulsor speed.

Compared with piston engines, turbines have different performance characteristics because they utilize different approaches to thermal-mechanical energy conversion. As a result, the turbine engine offers such advantages as lighter weight, higher reliability, and less frequent maintenance. However, turbine engine efficiencies approach those of piston engines only at full load conditions at power levels greater than a few hundred thousand watts. Therefore, if the turbine system were designed for a low power level, for example less than 75,000 W (100 hp), it would consume more fuel than the corresponding piston engine. The tendency of the turbine engine to perform less and less efficiently as the design level is reduced is a result of increasing flow losses that accompany the reduction of turbine size. In addition, fuel consumption for a partly loaded turbine engine is greater than that of a piston engine, and this is a consideration for torpedo applications requiring multispeed capability.

For torpedo applications a comparison of turbine and piston engine performance should include an evaluation of noise characteristics, since they have been shown to vary significantly with torpedo propulsion system designs.

Turbine operating frequencies are generally high (5,000–50,000 Hz) due to high rotational speed (50,000–100,000 rpm) and the multiple elements involved, such as turbine blades, gear teeth, etc. Piston engine operating frequencies are lower (100–3,000 Hz) due to the lower rotational speed (3,000–5,000 rpm) and accompanying low firing rate, bearing race frequencies, etc. For these reasons the turbine would appear to be well suited to large torpedo applications where radiated noise at low frequencies is a primary concern.

In summary, the piston engine is preferred over the turbine for open-cycle lightweight torpedoes. The piston engine is efficient at full and reduced speeds. The turbine system consumes too much fuel and would probably fall short of the required running range. No improvements in the turbine system are foreseen that would correct this performance deficiency, however, turbine systems for heavyweight torpedoes have given acceptable performance in the past. Self-noise data are not available for comparing piston and turbine systems, but, the piston engine may have some advantage due to its lower rotational speed. Development risk is lower for the piston engine because of the extent of previous development and production.

Two-Phase Turbines

As with the conventional turbine, the two-phase turbine can be operated in either an open- or closed-cycle mode. The two-phase engine consists of a somewhat conventional turbine operating on a uniform two-phase mixture. The two-phase mixture may be achieved by intermixing a low-vapor-pressure hot fluid like oil, with a high-vapor-pressure cold fluid like water. The water vaporizes and the two-phase mixture is collected in a rotating pitot tube device. For open-cycle systems hot combustion gas is intermixed with a low-melting-point metal and expanded, and the liquid metal may be collected and recirculated. For a closed cycle the vapor is condensed and recirculated. The primary advantage obtained is good power and efficiency at a low peripheral speed. Thus neither excessive diameters nor rotative speeds are required for direct propulsion applications.

The materials required are about the same as for conventional turbines; however, stress problems are reduced significantly by an order of magnitude reduction in rotational speed. Cooling could be minimized in some applications by varying the ratio of the two fluids to control turbine inlet temperature. There are no special working fluid restrictions other than the mutual compatibility for the cycle application.

The primary advantage of the device should be in its speed/torque characteristics. Good efficiency and torque at relatively low rpm (1000–5000) and the capability of varying maximum torque and efficiency peaks by varying the mixture ratio are the primary attributes. The thermodynamic efficiency is claimed to be high, but this has not been fully evaluated. Due to the low rotative speed lubrication problems associated with seals and bearings should be eliminated. For power density a number of 500 shp/ft^3 is quoted by previous developers. This includes the two-phase nozzle and turbine and should be compared to the reaction chamber or boiler, turbine, and speed reducer for a conventional turbine for a given application. Simplified open- and closed-cycle system schematics are shown in Fig. 15.

The basic limitations are that the turbine wheel may be somewhat larger, an inventory of two fluids must be carried, and the state of development is low. Basic efficiencies and power densities have not been clearly demonstrated. Also the two-phase nozzle efficiency could require further development. Expertise in this area currently resides at Bi-Phase Engines, Santa Monica, CA.

Bladeless Disc Turbine

The bladeless disc turbine consists of a turbine without a conventional bladed or vaned rotor. The device consists of a rotor constructed of a number of thin discs mounted on a shaft as shown in Fig. 16. In most aspects this device should be comparable to a

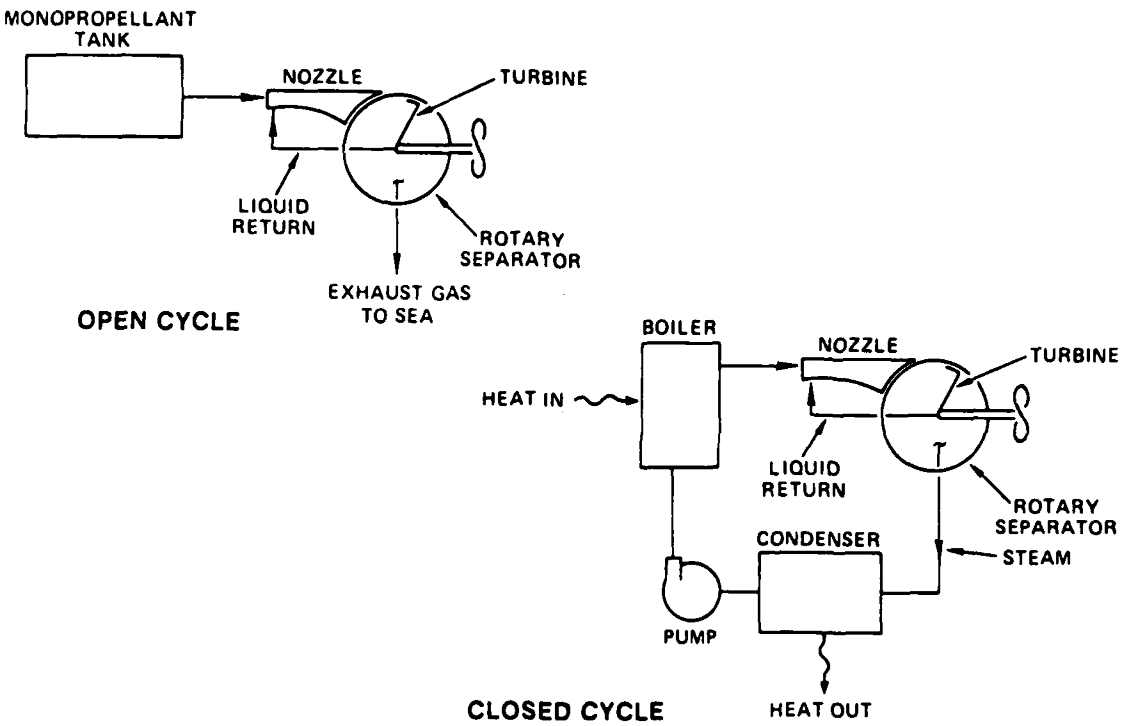


Figure 15. Two-phase turbine propulsion systems.

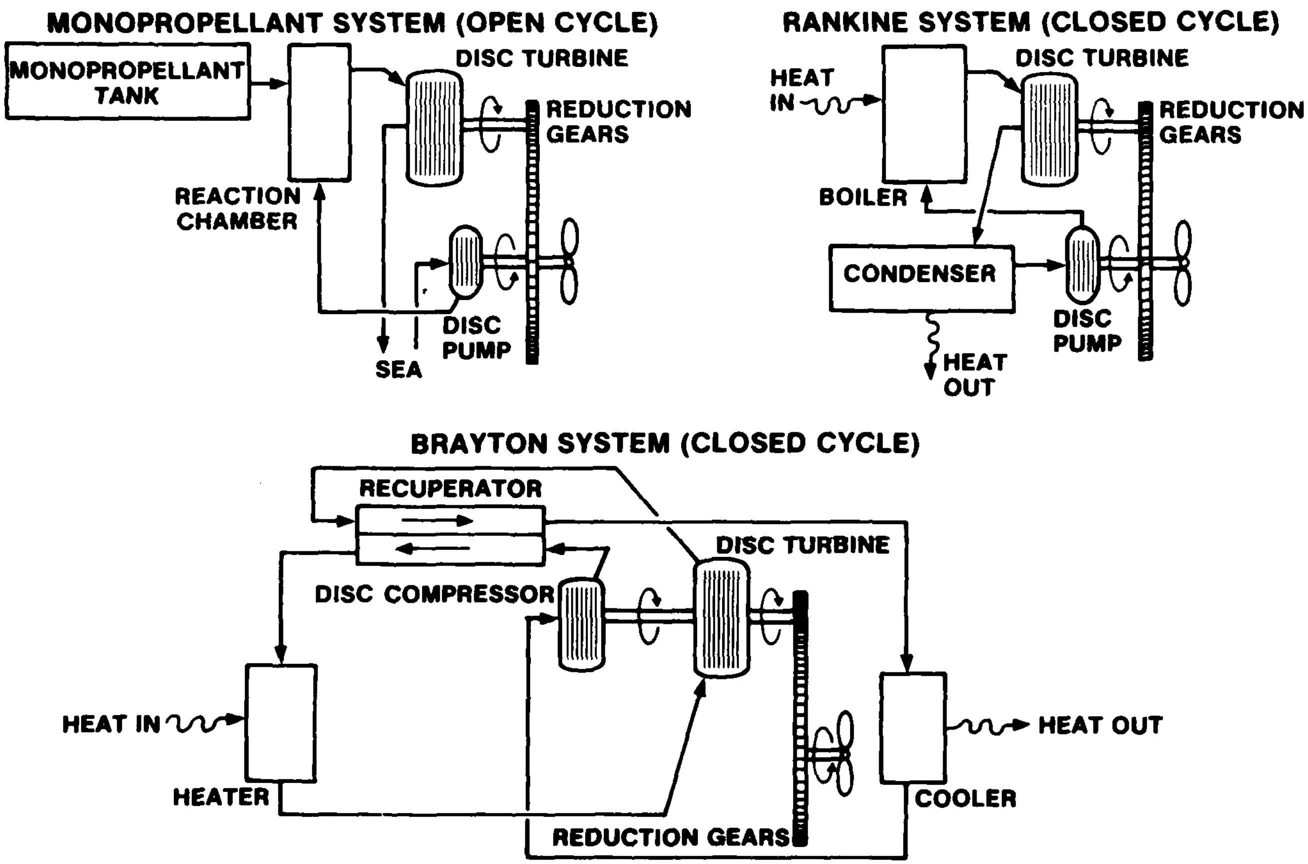


Figure 16. Potential torpedo propulsion system using disc turbomachinery.

conventional turbine, although higher temperature working fluids may be used by employing high-temperature materials. This has the advantage of producing higher efficiencies but at some cost in volume. For some applications where cooling is a problem this device could be advantageous. High power-to-weight and -volume ratios require high peripheral speeds, so that for torpedo-like applications a speed reducer would be required. Lubrication of bearings should be similar to a conventional turbine.

Specific fuel consumption and turbine efficiency have not been evaluated except in crude models not optimally designed. Optimum design parameters are anticipated from a compressible flow model being developed by Dr. Charles Bassett (formerly of NOSC). Power density similarly has not been thoroughly evaluated, however, the design has a modular characteristic in that more discs may be added for more power. It is anticipated that a prime application would be high temperature, and/or dirty working fluids once good efficiency and power density are demonstrated. Radiated and self-noise characteristics, as with most new systems, are almost totally unknown and would depend mainly on proper design of bearings, balancing, and speed reducer. Without blades, however, certain line spectra associated with the blades would not appear.

At this time the device must be considered to be in the exploratory development stage, with theoretical models and demonstration prototypes being constructed. There is no existing industrial base. Cost should be comparable to or lower than a conventional turbine since the basic design is quite simple.

OPEN-CYCLE SYSTEMS SUMMARY

Open-cycle monopropellant propulsion systems are in wide use in the Fleet today. Both lightweight and heavyweight torpedoes use Otto Fuel with piston engine expanders, the lightweight with a counterrotating engine driving counterrotating propellers, and the heavyweight with a single shaft output driving a pump-jet. (A turbine system was initially operated in the heavyweight torpedo program.) In addition, there have been other engine designs operated on Otto fuel over the years in experimental work, one being run in a modified lightweight torpedo to a depth of several hundred meters at very high speeds. Piston engine design and development expertise resides primarily with Gould, Inc., Cleveland, Ohio. The corresponding open-cycle turbine engine expertise is held at Sunstrand Energy Systems, Rockford, IL.

In addition to Otto Fuel, which is currently in the Navy logistical system, other monopropellants are under development. Eventually one of these may replace Otto Fuel because of its lower toxicity and cleaner burning characteristics, even though energy improvement may be minor. Other fuels in the experimental phase would provide a wakeless replacement.

CLOSED-CYCLE THERMAL SYSTEMS

Over the years, a number of high-energy, bi-propellant torpedo propulsion systems have been investigated by in-house Navy laboratories and industry. Currently, only one bi-propellant program is active to the point where it could be considered for lightweight torpedo applications. That program is SCEPS, Stored Chemical Energy Propulsion System. SCEPS is a closed-cycle (Rankine) steam loop heated by the highly energetic reaction of molten lithium (Li) and sulfur hexafluoride (SF_6). The equation for the reaction is:

$$8\ Li + SF_6 \rightarrow Li_2S + 6\ LiF + 20{,}000\ \frac{BTU}{lb - Li}\ .$$

An important aspect of this is the high heat of reaction. On a reactant volume basis, this is comparable to that of a liquid oxygen/liquid hydrocarbon combination.

The basic elements of the system are a boiler-reactor, turbine/gearbox, feedwater pump, and skin condenser. It also contains an oxidant system, speed control system, start system, and limit and check system. The Li-SF_6 reaction heats water in the boiler to make high-pressure, superheated steam, which is then expanded through the turbine. The low-pressure turbine exhaust steam flows to the condenser, where it is cooled and condensed to liquid water, rejecting heat to an external sink. The liquid water condensate is pumped to a high pressure by the feedwater pump and returned to the boiler to complete the cycle.

Figure 17 is a schematic illustration of the closed-cycle system in a torpedo-like configuration showing the principal elements. SCEPS is attractive since it is wakeless, efficiency is independent of depth, it is quiet by virtue of being a closed-cycle system, and has high energy and power densities.

SCEPS was originally conceived and pursued by TRW in the early 1960's and more recently has been taken over exclusively by the Applied Research Laboratory, Pennsylvania State University (ARL/PSU). As mentioned, the propellant system is lithium and sulfur hexafluoride (SF_6). The lithium is carried as solid metal fuel inside a reactor chamber prior to startup and as a molten mass after ignition. The SF_6 oxidizer is stored as a liquid under pressure, and bled into the reactor as a gas during operation. The reaction products are entirely solid and more dense than the reactants so that the heat-producing reaction occurs

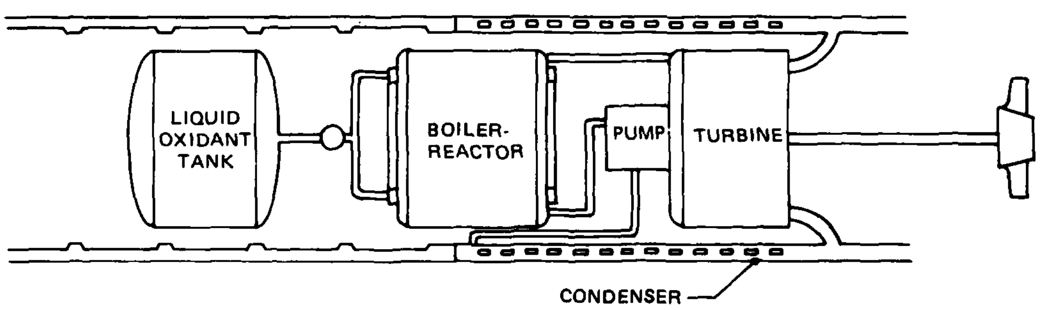


Figure 17. SCEPS schematic.

in a sealed reactor chamber entirely independent of ambient depth. Likewise, no gaseous wake is produced. Steam tubes form the walls of the reactor by helically winding them into an annular vessel, as shown in Fig. 18. This comprises the heat exchanger section of the closed Rankine cycle for the working fluid (water/steam), with the inner set of coils acting as the boiler and the outer set providing superheat. Early in the SCEPS program, a piston expander was built for the Rankine loop, but a turbine/gearbox is now used.

A number of advantages characterize the SCEPS system. The oxidizer, SF_6, is a safe, non-toxic gas under ambient conditions stored under its own vapor pressure at about 2.42×10^6 N/m^2 (350 psia), and is used as a dielectric for arc suppression in industrial applications. The SF_6 only becomes reactive at elevated temperatures, even with the lithium fuel. Acceptability of this high-energy oxidizer by Navy safety standards is a key factor in its favor.

The fuel, lithium, is a water-reactive alkali metal that melts at 181°C (357°F), and becomes dangerous if spilled into water while molten. However, when reasonable precautions are taken, such as storage in the protective reactor chamber, lithium should be certified as acceptably safe.

The system currently under consideration uses a turbine inlet pressure of 6.9×10^6 N/m^2 (1000 psia) and a turbine inlet temperature of 538°C (1000°F). The turbine exhaust pressure is 1.04×10^5 N/m^2 (15 psia). For these operating conditions the ideal Rankine cycle conversion efficiency is on the order of 33%. The steam turbine has an efficiency of roughly 63%, thus the actual Rankine cycle conversion efficiency is about 21%.

One disadvantage of the closed-cycle system is that it does not have the virtually instantaneous start capability of an open-cycle thermal system. Accordingly, fast-start experiments have been one focal point of a major phase of the development program. As indicated, upon ignition the fuel charge must be melted and brought to a high temperature. Cold water, injected at ignition must also be heated to its boiling point and then vaporized before any steam output is attained. Thus a considerable thermal inertia must be overcome before power is developed.

System characteristics are such that 2×10^6 N/m^2 (300 psi) steam pressure at turbine inlet will result in output power in excess of that required for half speed. Start-up time has been taken to be the time required to attain this pressure at turbine inlet. Bath temperatures on the order of 816°C (1500°F) have been obtained in about 3/4 sec and pressure versus time curves indicate a start time of slightly under 3 sec. Virtually no pressure rise occurs until approximately 2-1/2 sec, and then a very rapid rise occurs. This delay is attributed to the time required to inject and boil the initial water charge.

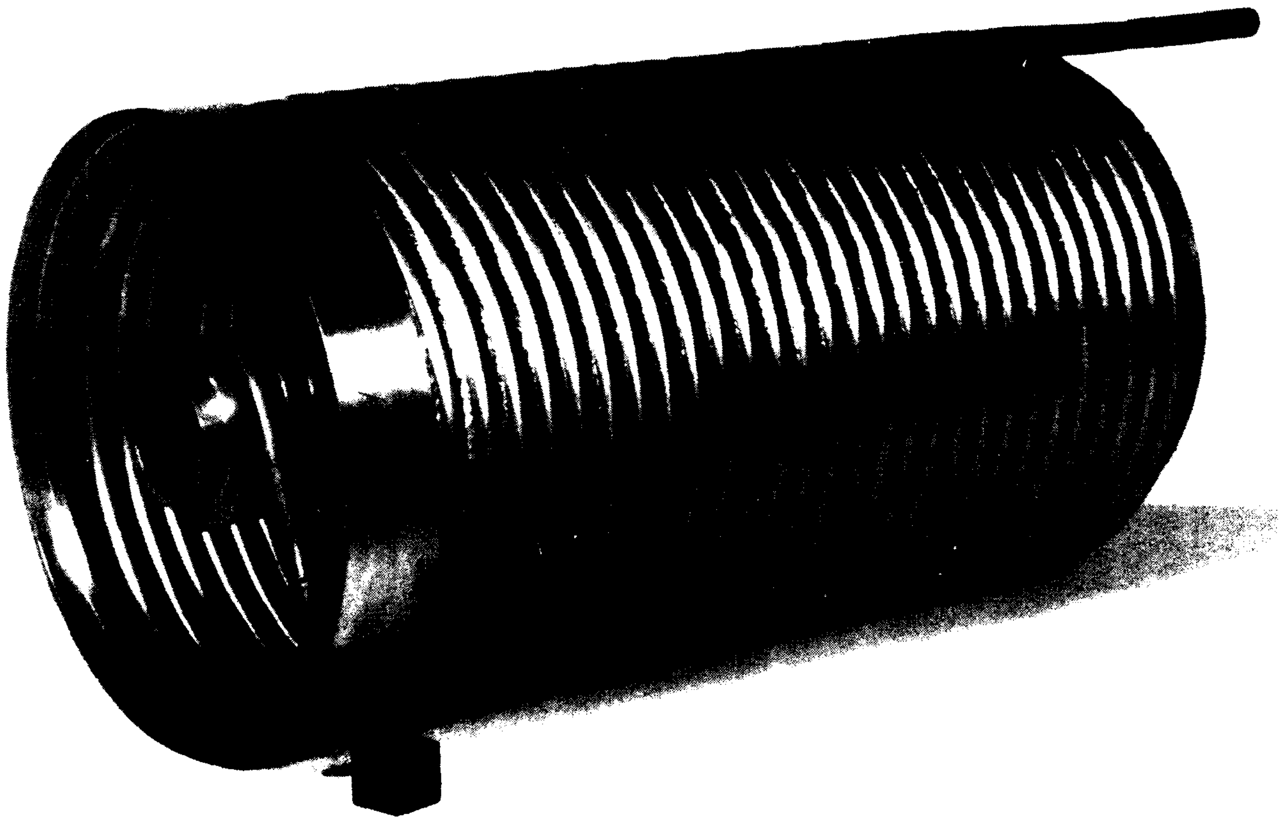


Figure 18. SCEPS boiler reactor.

CONCLUSION

Closed-cycle propulsion systems are desirable for torpedo applications because of their wakeless operation and depth-independent performance.

Most of the development to date on SCEPS has been devoted to perfecting the Li-SF_6 reactor system, which now appears to be well in hand. An experimental system, similar to Fig. 19. has been packaged by ARL/PSU and demonstrated in a test torpedo.

The SCEPS propulsion system is one of the few programs now active which can be considered truly "high-energy." The excellent specific energy, on both a weight and volume basis, is very attractive for high-speed, long-endurance torpedoes. The chemical reaction is inherently wakeless, and the propellants can be considered acceptably safe.

On the other hand, the overall system is complex by torpedo power plant standards and represents a new concept for torpedo propulsion. Substantial engineering will be required to package the necessary components compactly, particularly in a small-envelope torpedo, and to achieve acceptable levels of reliability.

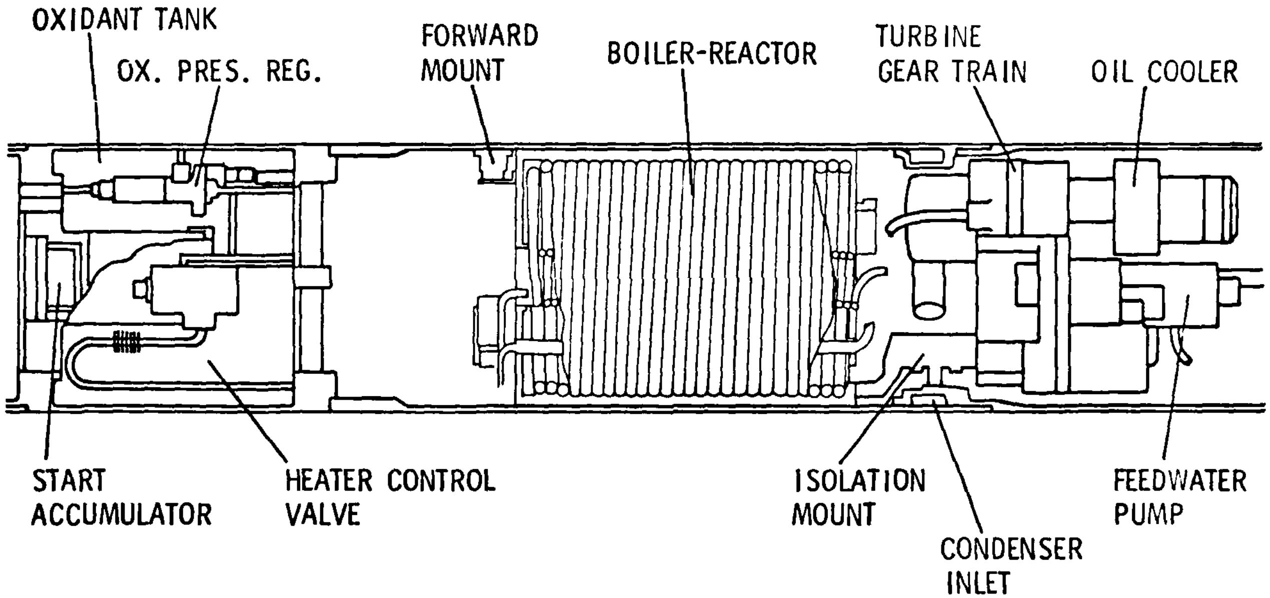


Figure 19. SCEPS power plant.

CONCLUSIONS ON PROPULSION CANDIDATES

Different propulsion systems, currently under development, have been discussed for consideration for advanced development in future lightweight torpedoes. Three basic types of systems were considered; electric, open-cycle, and closed-cycle (SCEPS). All three types can be operated at extended depths, although a depth penalty is incurred with the monopropellant open-cycle system. SCEPS is completely wakeless, as is the $LiSCOl_2$ battery system, and the hydrogen-evolving seawater and AlAgO batteries can be considered near-wakeless. While the more widely used monopropellant (Otto Fuel II) produces a sizable gaseous wake, other fuels are under development with substantially reduced wakes. Electric systems are typified as being inherently quiet, but experience has shown that thermal powerplants can be made acceptably quiet through proper design and electric systems can be noisy by reason of poor design.